Z-scan Measurement of Upconversion in Er:YAG

Jeffrey O. White, Thomas A. Mercier, Jr., John E. McElhenny Army Research Laboratory, 2800 Powder Mill Rd., Adelphi, MD 20783-1197

Carl E. Mungan

Department of Physics, U.S. Naval Academy, Annapolis, MD 21402-5002

Introduction

Cooperative, or energy-transfer, upconversion reduces the population of the $^4I_{13/2}$ manifold in Er:YAG, increasing the laser threshold, but not, in theory, the slope efficiency [1]. We have measured the cooperative upconversion parameter in Er:YAG using the z-scan technique as a function of Er concentration (0.5% to 5%) with the sample at room temperature (298 K) and 80 K. The value we obtain at room temperature is 2-3 times larger than previously reported [2,3]. The value we obtain at 80 K is approximately eight times larger than the value at room temperature.

An Er:YAG laser operating at cryogenic temperatures has recently produced 400 W at 1645 nm [4]. Knowledge of the low-temperature upconversion coefficient will allow further improvements in the design. It may also help explain the interesting temperature-dependent output power which peaks at ~160 K [5].

A previous measurement of upconversion relied on a short-pulse laser [2]. One advantage of the z-scan technique is that the measurement can be carried out with the same quasi-cw diode laser that will pump the Er:YAG laser being developed.

Model

A model including the lowest four manifolds of Er³⁺ was used to fit the data. Included in the model is a rate equation for the population of each manifold, e.g.

$$\frac{dN_1}{dt} = +\frac{I\sigma}{h\nu} (f_e N_2 - f_a N_1) + N_2 W_{21} + N_3 W_{31} + N_4 W_{41} + C_{up} N_2^2. \tag{1}$$

Here, N_1 (N_2) is the population of the ${}^4l_{15/2}$ (${}^4l_{13/2}$) manifold, I is the laser intensity, σ is the absolute cross section, f_a (f_e) is the probability that an ion in the ${}^4l_{15/2}$ (${}^4l_{13/2}$) manifold is in a sublevel that can <u>a</u>bsorb (<u>e</u>mit) a laser photon, W_{ij} is the relaxation rate from level I is level I, and I is the upconversion coefficient. Also included in the model is a propagation equation for the laser beam:

$$\frac{dI}{dz} = I\sigma(f_e N_2 - f_a N_1) = -\alpha I. \tag{2}$$

To account for the Gaussian intensity profile, the power is divided into eight equal portions associated with the peak intensity: I_p , $(7/8)I_p$, etc. The transmitted powers are then calculated separately as though at a uniform intensity, and then summed. The difference between eight slices and sixteen was negligible, so we used the former to speed the calculation.

Experiment

A DFB laser operating continuously at 1532 nm was amplified in a single mode fiber up to 3 W to provide the illumination. The duty cycle was reduced to 10% with a shutter operating at 1 Hz, to avoid heating the samples. An InGaAs photodiode and lock-in amplifier were used to detect the beam transmitted through the sample. The samples were 10 mm in diameter, 1 mm thick, and anti-reflection coated. The sample was placed in a cryostat for the 80 K measurements (Fig. 1).

a REPORT unclassified	b abstract unclassified	c THIS PAGE unclassified	Same as Report (SAR)	5		
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15. SUBJECT TERMS						
14. ABSTRACT						
13. SUPPLEMENTARY NO Proceedings of the	otes 13th Annual Direct	ed Energy Sympos	ium, 15-19 Nov 20	10, Bethesda	, MD.	
12. DISTRIBUTION/AVAIL Approved for publ	LABILITY STATEMENT ic release; distributi	ion unlimited				
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Naval Academy, Department of Physics, Annapolis, MD, 21402				8. PERFORMING ORGANIZATION REPORT NUMBER		
				5f. WORK UNIT NUMBER		
				5e. TASK NUMBER		
6. AUTHOR(S)				5d. PROJECT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
Z-scan Measurement of Upconversion in Er:YAG				5b. GRANT NUMBER		
4. TITLE AND SUBTITLE				5a. CONTRACT NUMBER		
1. REPORT DATE DEC 2010	2 DEDODE TYPE			3. DATES COVERED 00-00-2010 to 00-00-2010		
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Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and

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Form Approved OMB No. 0704-0188 The standard z-scan geometry was used [6], with a 20 cm focal length lens. The intensity profile was measured by translating a razor blade across the beam and fitting to the error function to determine the waist (Fig. 2a).

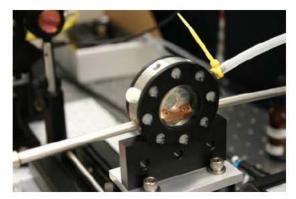


Fig. 1 10-mm diameter Er:YAG sample in the liquid nitrogen flow cryostat.

Results

The transmission of each sample as a function of position shows a peak where the beam intensity is highest, due to saturation of the absorption (Fig. 2b). The effect of upconversion is to lower the peak, because upconversion depletes the $^4I_{13/2}$ manifold, shifting the onset of saturation to higher intensities.

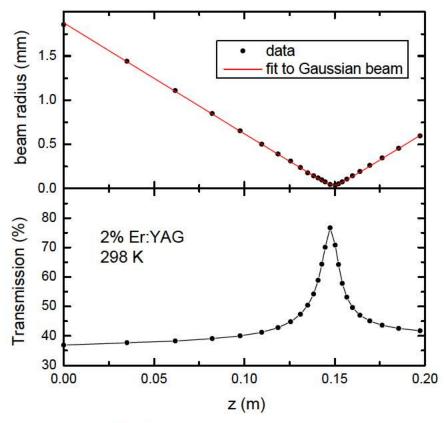


Fig. 2 (a) beam radius as a function of position, (b) transmission of a 2% Er:YAG sample at 298 K.

The shift can be clearly seen in a plot of effective absorption coefficient vs peak intensity (Fig. 3). $\alpha_{\rm eff}$ is calculated from experimental data (symbols), and plotted, along with the simulation curves for $C_{up} = 0$ (dashed line) and for $C_{up} = 1.5 \times 10^{-17}$ cm³/s (solid line). The different symbols correspond to runs at different power levels. We estimate the accuracy to be approximately a factor of two in C_{up} .

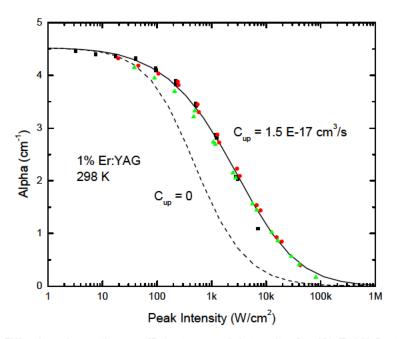


Fig. 3 Effective absorption coefficient vs peak Intensity, for 1% Er:YAG at 298 K.

For a 1% sample at 80 K, our data indicate a value of $C_{up} = 8 \times 10^{-17} \text{ cm}^3/\text{s}$ (Fig. 4). These are the first reported measurements of Er:YAG upconversion at cryogenic temperatures.

We find that $C_{\rm up}$ is approximately proportional to [Er] at both temperatures (Fig. 5). A linear fit to the four samples at room temperature would indicate a $C_{\rm up}$ value of 1.0×10^{-17} cm³/s for the 1% sample. A value of 5×10^{-18} cm³/s was previously obtained with a time-dependent method based on the non-exponential decay of luminescence from the $^4I_{13/2}$ level [2]. A value of 3.5×10^{-18} cm³/s was obtained with a steady-state method based on the upconversion-induced change in lasing threshold [3].

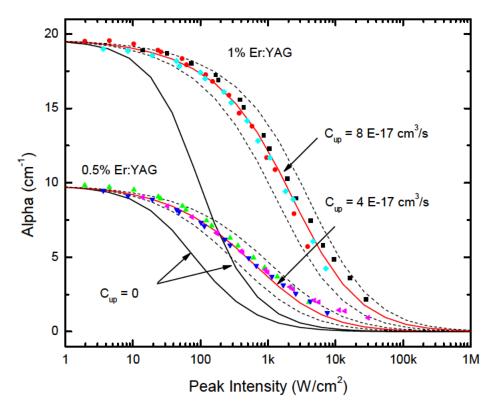


Fig. 4 Er:YAG z-scan experimental data obtained at 80 K, for 1532 nm (symbols). The curves are simulations for different values of C_{up} . The dashed lines represent values of C_{up} that differ from the red lines by a factor of two.

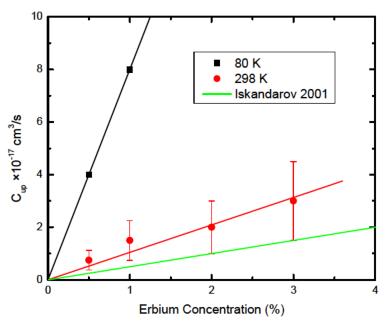


Fig. 5 Measured upconversion coefficient as a function of [Er] for 80 K and 298 K, along with a linear fit. The green line is a linear fit to the low concentration results from Ref. 2.

Conclusion

Z-scan measurements on Er:YAG have been made at room temperature and 80 K. The data have been interpreted with a steady-state model including rate equations for the (intensity-dependent) populations of the lowest four manifolds, and an equation for the (population-dependent) propagation of the light. Our room temperature results for $C_{\rm up}$ are approximately twice the values previously obtained with other techniques. Our values for $C_{\rm up}$ at 80 K are the first obtained at a cryogenic temperature, and are approximately eight times larger than at room temperature.

High power Er-doped lasers for eye-safer applications are currently being designed to operate at cryogenic temperatures because the optical, thermal, and mechanical properties of Er:YAG, for example, improve as the temperature is lowered, depending on the particular transitions involved. Knowledge of the low-temperature $C_{\rm up}$, and its dependence on Er concentration will allow the effect of upconversion to be minimized by choosing the optimum doping level. An advantage of the z-scan technique for measuring upconversion is that it can be carried out with the same quasi-cw diode laser that will pump the solid-state laser being designed.

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